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Pinniped Hearing in Complex Acoustic Environments

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LONG-TERM GOALS

Pinnipeds (seals, sea lions, and walruses) are amphibious marine mammals that are susceptible to coastal anthropogenic noise. The long-term goals of this effort are to improve understanding of (1) the sound detection capabilities of several pinniped species, and (2) the effects of noise exposure on the sound detection capabilities of these species. The laboratory and field studies associated with this research will reveal certain aspects of how amphibious mammals receive, perceive, and recognize acoustic information in background noise and will contribute broadly to current knowledge of marine mammal bioacoustics.

OBJECTIVES

Improve understanding of hearing in pinnipeds by extending psychoacoustic profiles of sound reception obtained from simplified auditory processing tasks to those describing performance under increasingly complex acoustic conditions. Relate laboratory measurements to concurrent field studies of communication in fluctuating natural noise backgrounds. Strengthen predictive models that describe how signal structure and noise environments interact to constrain auditory performance, and develop weighting functions that can be used for species-typical acoustic risk assessments.

APPROACH

Psychoacoustic measurements of hearing are obtained from California sea lions, harbor seals, and northern elephant seals under highly controlled laboratory conditions. Long-term captive subjects are trained using operant conditioning procedures to report the presence or absence of auditory signals in noisy or quiet backgrounds. Because the sensitivity and frequency range of hearing in pinnipeds varies significantly as a function of medium, testing takes place both under water (in a mapped, reverberant acoustic field) and in air (in a sound-attenuating hemi-anechoic chamber). The stimuli presented during testing comprise synthetic and natural sounds that are systematically varied in spectral and temporal complexity. The general approach is to obtain absolute detection thresholds for specific complex sounds and compare these thresholds to those previously obtained for pure-tone signals. The tasks are then repeated against a variety of synthetic and natural background masking noises to determine the

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signal-to-noise ratios that limit auditory detection. The methods are modeled in part from studies of bird communication in noise (Dooling et al., 2009; Lohr et al., 2003) and build upon previous research in our laboratory on hearing capabilities and cognitive processing of sensory information.

Field measurements of representative species-typical vocalizations and associated ambient noise are made at pinniped breeding rookeries, and simple propagation models of natural signals through representative environments are generated. The data collected include physical measurements of environmental noise (maximum and equivalent continuous sound pressure level over different time scales) and vocalization parameters (source level, spectral composition, call duration, inter-call interval). These data are combined with information about individuals (age, sex, identity, size, reproductive state, dominance status, and spatial movements) so that functional communication can be assessed through field experiments. Collectively, the complementary laboratory and field studies allow effective detection and recognition ranges for biologically relevant sounds to be modeled under various conditions of natural and anthropogenic noise.

Key personnel on the project in FY2013 included the PI, research technician Asila Ghoul, UC Santa Cruz graduate students Jillian Sills and Kane Cunningham (Ocean Sciences) and Caroline Casey (Ecology & Evolutionary Biology), and animal technician Jenna Lofstrom. The field data were collected by the PI and Caroline Casey with collaboration from Brandon Southall, a research associate at UCSC. The entire research program was supported by a team of 18 undergraduate and post-graduate volunteer research assistants and interns who received formal training in marine mammalogy and bioacoustic research in exchange for their apprenticeship in our laboratory at the University of California Santa Cruz.

WORK COMPLETED

Work completed in FY2013 focused on the abilities of seals and sea lions to detect sounds with complex spectral and temporal features in both masked and unmasked conditions. Two major studies were conducted along these lines.

(1) The abilities of one California sea lion and one harbor seal to detect complex sounds in quiet conditions were investigated. A set of complex signals was synthesized with the goal of isolating three common features of natural sounds: amplitude modulation, frequency modulation, and the presence of multiple harmonics. While a single natural sound will often include more than one of these complex features, by isolating each into a separate signal we are able to gain insight into the effect of each on signal detection thresholds. Signals were synthesized at a range of frequencies designed to span the functional hearing ranges of these species, and detection thresholds were measured under water for each of these signals. For comparison purposes, *a priori* detection threshold predictions based on the audiograms of these subjects were calculated. Because the audiogram is based on simple, narrowband stimuli, we hypothesized that detection thresholds would be lower for more complex stimuli. This hypothesis was based on a growing body of literature concerning structures within the mammalian auditory system seemingly designed to take advantage of features of natural sounds (*e.g.* Nelken *et. al.*, 1999).

(2) The ability of one harbor seal to detect complex sounds in noisy (masked) conditions was investigated. This study of masked thresholds built on the above study of absolute detection thresholds for complex sounds. A similar set of complex sounds was used, this time focusing on the lower frequency region of the functional hearing range, where anthropogenic noise-energy is often

concentrated. Two noise conditions were investigated: a flat-spectrum white noise, typical of maskers used in traditional audiometrics, and a recorded sample of shipping noise exhibiting a higher degree of temporal fluctuation and coherent amplitude modulation relative to the white noise condition. Results were compared to typical critical ratio measurements, calculated using narrowband, tonal signals in white noise bands, made specifically for this study. We hypothesized lower critical ratios for complex sounds based on literature describing masking release due to enhanced stream-segregation abilities in the presence of complex acoustic features (*e.g.* Branstetter *et. al.*, 2013; Hall *et. al.*, 1984).

These two studies combined form a basis for understanding how pinnipeds perceive complex sounds in the natural environment. The resultant data also provide information required for predicting the effects of anthropogenic noise on pinnipeds and other marine mammal species.

(3) In addition to these experimental studies, research was also conducted in FY2013 on age-related hearing loss in the context of a long-term (20 year) study of hearing in sea lions.

(4) In the field, extensive sampling of male northern elephant seal vocalizations was conducted on four different rookeries in California during the 2012-2013 breeding season.

RESULTS

(1) The accuracy of *a priori* predictions based on audiogram data varied according to stimulus type as well as by subject. In general, FM stimuli were best predicted by audiogram data, while predictions for harmonic stimuli were the least accurate. The accuracy of predictions for AM stimuli varied by subject.

FM stimuli Absolute detection thresholds for FM signals were well predicted by the audiogram. *A priori* predictions were made based on linear interpolation of the two nearest audiogram data points for each subject that bracketed the center frequency of the FM sweep (audiogram data based on Reichmuth *et. al.*, 2013). All observed thresholds were within 5 dB of the predicted value for both subjects, with the exception of the sea lion threshold at a 38 kHz center frequency, which was 7 dB lower than predicted.

AM stimuli Absolute detection thresholds for AM signals were well predicted by the audiogram for the California sea lion, but not for the harbor seal. *A priori* threshold predictions were made based on linear interpolation of the audiogram at the carrier frequency. All observed thresholds were within 5 dB of the predicted value for the California sea lion. Thresholds observed for the harbor seal varied less than expected with changes in the carrier frequency. While the predicted thresholds for this subject and this stimulus varied by 12 dB across carrier frequencies, his measured thresholds for all four carriers were within 5 dB of one another, possibly indicating that, for this animal, the characteristics of the envelope, which remain constant across stimuli, were more relevant to detection than the frequency of the carrier signal. Further work is needed to determine if this is a trait that varies by species, by individual, or both.

Harmonic stimuli Absolute detection thresholds for harmonic stimuli were lower than predicted for both species and both fundamental frequencies. *A priori* predictions were made based on the minimum threshold for any of the individual harmonics contained within the signal. The difference between threshold predictions and observations ranged from 1 to 12 dB. These results are interesting not only relative to concerns about ocean noise, but also relative to how the auditory system processes complex

signal features, including multiple harmonics. The fact that predictions based on what should be the perceptually loudest harmonic component are too high suggests that, in quiet conditions, detection of harmonic stimuli involves the simultaneous processing of information in multiple frequency channels. That is, the fact that detection occurs at sound pressure levels where all of the individual harmonic components should be undetectable implies that information is being integrated across critical bands, at levels below the narrow-band thresholds for the individual frequency components, to determine the detectability of a signal.

(2) In this masking study, the detection thresholds for the harbor seal subject exhibited a high degree of variability relative to predictions made based on traditional critical ratio measurements. These differences from predicted sensitivity spanned a range of over 14 dB, from a 2 dB decrease in sensitivity to a 12 dB increase in sensitivity relative to predicted values. The two kinds of broadband stimuli (octave-band FM sweeps and harmonic complexes) resulted in the greatest relative increases in sensitivity. This result indicates that the subject's auditory system has the ability to integrate information from across auditory channels to aid in detection in noisy environments, consistent with similar findings in human and cetacean subjects (*e.g.* Hall *et al.* 1984, Branstetter *et al*., 2013).

The shipping noise condition resulted in a greater degree of deviation from predicted values relative to the white noise condition. This could be a result of increased temporal fluctuations relative to the white noise condition, including a degree of comodulation exhibited by this masker. Further, the presence of amplitude modulation in the masker seems to have resulted in information masking when combined with the AM stimuli resulting in a 3 dB decrease in sensitivity relative to the predicted value. Similar work is ongoing for a California sea lion subject.

(3) Hearing loss attributable to aging was documented in a 28-year-old female California sea lion that has been tested regularly over a 20 year period in both air and water. This sea lion showed hearing losses in water at all frequencies, with the greatest losses (+50 dB) at the highest frequency that could be tested (15.4 kHz). Equivalent losses at each frequency were expressed in air.

(4) In the field, extensive sampling of male northern elephant seal vocalizations was conducted on four geographically separated rookeries in California during the 2012-2013 breeding season. A total of 1154 vocalizations were obtained from male elephant seals at Año Nuevo, Piedras Blancas, Point Reyes, and San Nicolas Island. These data indicate peak call amplitudes exceeding 120 dB re 20 µPa, peak spectral energy <1000 Hz, and inter-pulse intervals between 0.9 and 2.4/s. A subsample of these data will support our effort to characterize the call patterns present within breeding locations along the California coast. We will test the specific hypothesis that there are unique, site-specific dialects between elephant seal breeding colonies that have persisted as the species has recovered recent exploitation; these analyses are ongoing.

IMPACT/APPLICATIONS

The audiometric data generated by this project and preceding ONR supported projects have contributed to noise exposure criteria developed specifically for free-ranging marine mammals, which in turn are used by the operational Navy, industry, U.S. and International regulators to establish appropriate guidelines and mitigation for anthropogenic noise emissions in marine environments. We expect that results of the complex detection and masking experiments will aid in the future development of masking models of anthropogenic noise effects on marine mammal communication.

We also believe that because this work encompasses a wide variety of stimulus types, it will serve as a roadmap for future research concerning how pinnipeds and other marine mammals perceive complex sounds.

RELATED PROJECTS

Psychoacoustic measures of hearing in Southern sea otters (*Enhydra lutris nereis*): underwater sound detection thresholds and critical ratios. C. Reichmuth (UC Santa Cruz) is the PI; the project is supported by NAVFAC through HDR Inc. This project expands upon auditory research with pinnipeds by examining hearing in another marine carnivore, the southern sea otter. There is some overlap in facilities, experimental resources, and personnel.

Airgun Effects on Arctic Seals: Auditory Detection, Masking, and Temporary Threshold Shift. C. Reichmuth (UC Santa Cruz) is the PI; the project is supported by the Joint Industry Programme on Sound and Marine Life. This project expands upon auditory research with pinnipeds by examining hearing and the effects of noise in arctic seals. There is some overlap in facilities, experimental resources, and personnel.

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